ECONOMIC ESTIMATES

1.0 INTRODUCTION

Society is faced with the difficult task of balancing the benefits it may gain by reductions in pollution levels against the economic and social costs of obtaining those reductions. To facilitate finding the proper balance, the relationships between pollution and its effects are often stated in common terms. The quantitative expressions of such relationships in monetary terms are called economic damage functions.

Economic theory states that a control policy is optimal if the marginal benefits due to pollution abatement is matched by the marginal expenditure incurred to implement the control.[1] The benefit due to pollution abatement is commonly stated as the inverse of the dis-benefit or cost of the damage due to the pollutant in question.

While the assignment of monetary value to such pollution-related effects as illness, ecological diversity or even life itself is a controversial approach, monetizing damage to non-living materials is seen as inherently more acceptable and appropriate. Even though materials damage is only a part of the total dis-benefit of pollution, its quantification is an important part of the overall analysis of costs.

Unfortunately, the current ability of society to accurately relate the costs of damage to materials to the level of ambient pollution is poor. There are great uncertainties about the physical mechanisms and degree of the damage attributable to pollutants, even greater uncertainties about the economic impact of that damage and much fundamental information such as the level of ambient pollution itself, is often inadequate. The existing state-of-the-art for employing economic damage functions in rational decision making is such that only crude, qualitative use of such results is appropriate.

Economic estimates of the costs attributable to some of the damaging effects of sulfur oxides and particulate matter on materials are available from the literature. Some of these estimates were derived directly from consumer or business surveys. Others were derived from estimates of maintenance and replacement costs based upon available damage functions and ambient air data. Extrapolation of these study results for application to the present situation is not easily done, and in some cases cannot be done with accuracy, since both fluctuations in the value of the dollar in the intervening years and changes in air quality must be considered in any such adjustment of past reported dollar cost of materials damage. Therefore, in the present document, all dollar costs assigned to materials damage and soiling are given as reported.

Table 1 presents a summary of the Consumer Price Index for the years from 1966 to 1980. In the table, 1967 is used as the base year and is set at 100. All other years reflect prices relative to 1967.

TABLE 1. INFLATION ADJUSTMENT

1980	251.7
1979	217.4
1978	195.4
1977	181.5
1976	170.5
1975	151.2
1974	147.7
1973	133.1
1972	125.3
1971	121.3
1970	116.3
1969	109.8
1968	104.2
1967	100.0 (Base year)
1966	97.2
1965	94.5
1964	92.9
1963	91.7

2.0 TYPES OF ECONOMIC DAMAGE

The costs of air pollution damage to non-living materials fall into three general categories: direct damage costs, avoidance costs and aesthetic or psychic costs;[2] each of these categories quantified in monetary terms. However, the complexity of determining those costs increases with the extent that human judgment plays a role in the actions taken.

When physical damage has proceeded to the point where the material in question no longer serves its intended function, the cost of that damage can be directly derived from the cost of replacement or repair of the material. For example, when a metal storage tank becomes so corroded due to pollutant damage that it begins to leak, the cost of fixing the leak or of replacing the tank is obvious. The human judgment factor is primarily concerned with the desirability of having the storage tank at all. The direct damage has a direct response, and the direct response engenders a direct cost.

In real-world practice, however, allowing materials to degrade until they no longer fulfill this primary function is seldom the norm. The value of a structure or a system is usually greater than the simple sum of its component materials. Accordingly, it is common practice to expend effort and money to avoid deterioration if the continual use of the overall structure is important. Protection of damage-susceptible material or substitution with similar but more resistant materials is the usual alternative. When the protection or substitution results in higher costs, those costs can be attributed as an avoidance cost of the damage.

Avoidance costs are harder to accurately quantify than direct damage costs. Human judgment is needed to determine the best strategy for avoiding damage.

The problem is especially acute when substitution of different materials is considered. The new material often has different properties beyond increased resistance to damage by pollutants. For example, if a stainless steel tank is substituted for an ordinary carbon steel tank, a whole collection of physical properties changes. The method of fabrication, the basic design, size, or shape may be different in turn. The non-reactive nature of stainless steel may make it a superior container for the substances stored within it. If the stainless steel tank is more desirable than a carbon steel one for a number of reasons, the fraction of the cost which should be assessed to its increased resistance to atmospheric pollution may be hard to quantify.

Similarily, protection of a susceptible material can change more than the reaction to pollutants. Painting a surface can also change its color or appearance. Determining the fraction of the full cost of the paint job attributable to the increased resistance to pollution it affords the substrate is not a simple task.

It should also be noted that the paint can be considered a material susceptible to pollutant damage in its own right. It, in turn, can be the subject of direct damage costs in the case where replacement (re-painting) is necessitated by pollutant damage, or of avoidance costs when a more expensive formulation is substituted for one with less pollution resistance.

Aesthetic costs are by definition based on human judgment. They are also the most difficult to quantify and are the most variable with location and/or time. Despite their somewhat subjective basis, such costs are important in assessing the dis-benefits of pollution.

Aesthetic costs are, at least in part, reflected by the costs paid to avoid them. People are willing to pay to maintain or restore a material to a state which has little to do with its ability to perform its primary function. A metal storage tank holds as much whether its outer surface is clean or dirty. Yet, the increased cost of keeping it "reasonably" clean reflects the fact that there is some psychic cost in seeing it dirty.

Quantifying this psychic cost is extremely complicated. The price paid to avoid the psychic cost is real, but it is also a function of changing notions as to what is "acceptable". The willingness to pay is often tempered by the ability to pay. Finally, the “acceptability" of a situation is often based on some dimly defined sense of economic utility. Rust stains may be unsightly because they indicate an underlying physical damage which could lead to loss of function of the material in question.

Aesthetic costs exist even if no monetary expenditure is made to eliminate them. However, they are nearly impossible to quantify accurately.

In summary, each category of cost contains some element of human judgment which influences the responses made to it. The more the human element is involved, the more difficult it is to quantify the cost in monetary terms. Economic damage functions which fail to account for the different types of costs do not provide useful information for decision-making.

3.0 METHODS FOR CALCULATING ECONOMIC IMPACT ON MATERIALS DAMAGE

3.1 COMPARATIVE APPROACH

There are two basic approaches for calculating the economic dis-benefit due to a given air pollutant; Comparative and Analytic.[3] Neither method is completely satisfactory. The Comparative approach compares the lifetime or maintenance costs for a given material in use in different ambient pollution environments. For the method to work, the environments should be similar in every respect, except for pollutant level. The total materials costs in each of the environments is determined and an economic damage function for the pollutant can be derived directly using the differences in materials costs and the differences in pollutant concentration.

There are several factors which make the comparative approach difficult to apply. The approach is highly sensitive to differences in the nonpollutant variables at each location. Since there are so many variables which can have a strong influence on materials damage and materials costs, it is extremely difficult to find locations that are truly well matched. Environmental and usage factors for the same material can be so different that the whole mechanism of damage may be changed. These problems lead to the necessity for examining a large number of matched environments in order to cancel out "random" errors. "Approximations" and "simplifying assumptions" can obliterate the true cost information being sought.

3.2 ANALYTIC APPROACH

The Analytic approach depends on laboratory or field-study derived physical damage functions and ambient air quality information. First, the specific interactions of the materials to be studied with the pollutants of interest must be delineated. The use of these materials and their value in society must be assessed. The exposure of the materials to pollutants and other environmental factors must be determined, as well as the effects of repair, replacement, protection, substitution practice, and the aesthetic sensitivity of the population concerned. The appropriate physical damage functions are used to quantify the physical damage due to a specific pollutant. The costs of that damage, relative to the degree of pollution actually present can then be calculated.

The success of the analytic approach is dependent on the accuracy of each of its component parts. Its chief drawback is the unavailability of needed data inputs. Much of the necessary information must be approximated or estimated from widely disparate sources. For example, the amount and value of materials in place in an area or on a nationwide basis is not readily available information, and the amount of material "in place" is a key input to economic damage functions.

In past studies, the amount of material exposed has been calculated by determining the amount produced during a period equal to the standard "use-life" of that material, and application of an "exposure factor' to account for the uses of which the material is put.[4] (The derivation of "exposure factors" is often surprisingly abritrary.)

Such a methodology has several major flaws. The most serious flaw is the inherent assumption that once a material is in place, it remains unchanged, except for deterioration. In some cases, such an assumption may be warranted, but in others it totally ignores the impact of practices related to avoidance costs and the changes in those practices with time. Galvanized steel is a good example. Not only has pollutant damage to galvanized steel been well studied,[5] such damage constitutes a major fraction of the costs attributed to pollution in many Materials Damage estimates.

Zinc coating is added to protect the steel from corrosion (note that the zinc coating would still be needed to protect steel against natural corrosion even if there were no man-made pollutants to consider). For many years galvanized surfaces were not otherwise coated due to poor paint adhesion. During the last 10 years, however, numerous paints and coatings have been introduced into the market which not only adhere to galvanized steels, but also offer excellent pollutant resistance. When bare galvanized steels may be susceptible to pollutant attack, coating such materials (especially for roofing and siding applications) is now common. When a galvanized steel surface shows signs of rust, it is now possible to avoid further damage instead of simply waiting until it is severe enough to warrant replacement. Therefore, although galvanized products are still in extensive use, the amount of zinc actually exposed to pollutants has greatly decreased; a factor not considered in most materials damage estimates to date.

The value of the material in place, or the costs associated with keeping it there, are likewise uncertain. Calculating the value of labor input to the cost of direct damage to a material is much more complicated than determining the cost of the material alone. Most studies to date have simply applied a "labor factor" to the overall estimate of the material replaced.[6] Since labor costs often dominate materials costs, any uncertainties or errors in estimating a "labor factor" have a major impact on the accuracy or certainty of the final cost estimate.

The reasons and schedules for maintenance activities can have a powerful effect on how the costs should be apportioned. For example, highway bridge steel is painted primarily to protect against corrosion. A physical damage function for attack by SO_2 on the paint can be derived. However, the paint is also subject to damage from rock impact, salt, and exhaust, etc. To resist damage from these much more severe damage agents, the paint is made especially tough and thick. Before air pollution can even begin to significantly affect the performance of the paint, it will usually have been damaged by the rocks, salt, or other environmental factors, such that maintenance action is necessary. The maintenance required by this other damage will also repair any minor damage that SO_2 might have caused. Therefore, the effect of SO_2 on the lifetime of the paint is minimal. The physical damage is below the threshold where it would have an effect on the bridge maintenance schedules or costs.

Similarly, children's shoes are rarely discarded because of SO_2 damage, although the leather may have a measurable damage function. It is possible to think of hundreds of other examples where a pollutant could cause damage, but other factors control the material's useful life. In assessing damage costs, proof of the existence of a damage mechanism by a given pollutant is not sufficient to say the damage is significant. If must also be shown that the pollutant has a real influence on the use life of the material.[7] Unless the analytic approach specifically takes into account the principal lifetime controlling factors, the damage cost estimates it generates are almost useless.

The usual practice when reporting costs based on the analytic approach is to give a range of error expected. Based on the accumulated uncertainties, the range of error often encompasses factors of ten or more.[7] Sadly, the statements of uncertainties are often overlooked when people begin to use the calculated values for decision making.

4.0 SPECIFIC ECONOMIC DAMAGE FUNCTIONS

4.1 CHOICE OF MATERIALS

So many materials are currently in use where they are exposed to pollution, it is not practical to attempt to quantify all damage costs due to all pollutants. There are two basic approaches to limiting the number of combinations to be considered. A number of materials could be chosen for study on the basis of their economic importance and the list limited by considering only those which evidence significant reaction with common air pollutants. Conversely, a list of materials which are known to respond to air pollution exposure could be drawn up, and the list subsequently limited only to those which are economically important. The key is that the final list should contain those materials for which pollution exposure has a serious impact on economic utlization. To warrant detailed study, a material should be both affected by the pollutant of interest <u>and</u> of economic importance. It makes little sense to detail the costs of damage that SO_2 does to buggy whips, even though the leather in them is susceptible to SO_2 damage. At the same time, too much effect should not be expended examining highway paving for oxidant damage just because highways represent major cost items.

Annual production figures have limited usefulness in determining the economic impact of a given material. Such figures do not take into account the use for which the material is intended, and do not include the costs associated with its utilization (installation labor, maintenance, etc.). Furthermore, use of such figures can lead to significant "double counting," (i.e., materials sold to producers of other materials).

Perhaps most importantly, if only materials with very high annual production are considered, materials with somewhat lower total production, but higher loss rate due to pollutant damage may be missed. This phenomena is particularly important if most of the turnover of the lower production material is due to pollutant damage.

Existing information about physical damage functions and previous studies claiming significant economic impacts of pollutant damage leads us to the list of materials in Table 2. In some cases, the designation of significant economic impact may be inaccurate or at best highly uncertain, but these materials are included in the discussion because the values reported have received such wide-spread note.

TABLE 2. ECONOMICALLY SIGNIFICANT MATERIALS SUBJECT TO POLLUTION DAMAGE

Paint
Structural metals
Electrical components
Fabrics
Plastics and elastomers
Non-metallic building materials
Works of art and historical monuments.

4.2 PAINT

Types of damage: Surface erosion, discoloration, soiling.

Principal damage-causing pollutants: sulfur oxides and other "acid" gases, particulate matter

Other environmental factors: moisture, sunlight, physical abrasion (wear), microorganisms.

Uses: The principal function of paint is to protect a subtrate and, as such, the cost of the paint and the labor and other costs associated with applying it can be considered an "avoidance cost" of damage to the substrate. However, a significant secondary function of paint is to enhance the external appearance of the structure or material to which it is applied. In this regard, paint is a "material" in its own right, and steps are taken to maintain its condition beyond that necessary for it to fulfill its protective function.

Because of this dual nature, care must be taken not to double count damage costs when paint is subject to attack by pollution. That is, the costs of damage to paint when paint is considered as a protective measure for a sensitive substrate such as carbon steel should not be totally counted as a cost of pollution if the cost of the same damage is to be counted as a loss of appearance of the paint itself.

Cost categories:

Direct: The most common type of action taken when one of the functions of a paint surface is impaired is to repaint or replace the paint. This approach is especially prevalent if the characteristic impaired is its protective function. Repair of a paint surface by "touch-up" painting or by cleaning of a soiled surface is sometimes practiced but is not as common since the labor costs can be close to those for repainting and the cost of the material itself is relatively small in comparison.

Avoidance: Paint as a material is not "protected" by the application of other materials or by changing its exposure to pollutants. The primary cost avoidance strategy is substitution. The formulation of the paint is changed and so a "new" paint is substituted. Note that substituting a completely different type of material (e.g., aluminum siding) in place of paint as a way to protect the substrate structure is not a case of "substitution" for paint *per se*. If a different type of material is used, the properties of the system are such that the discussion no longer involves paint at all. Just as the automobile cannot truly be considered a "substitute" for the horse or the horse a "substitute" for human legs, a major change in the nature or category of a material is more than a substitution. The portion of costs related to air pollution damage associated with a major substitution should be considered as an alternate protection strategy for the substrate being protected. These changes generally show up in the consideration of the amount of material in place.

Aesthetic: As with most disamenities, damage to paint is difficult to quantify monetarily. Some idea of the value of the aesthetic properties of a well maintained painted surface can be obtained by analyzing the direct and avoidance costs for damage to the non-protective aspects of paint. That is, the fact that society in general is willing to pay to maintain painted surfaces in a clean condition indicates there is a psychic penalty paid by those who see it dirty. However, since the acceptability of a given condition varies widely among individuals and with time, and with many other subtle influences, it cannot generally be quantified with any confidence.

Previous studies: Spence and Haynie[8] presented a survey and economic assessment of the deterioration of exterior paints ("trade paints") caused by air pollution. Included in this category were both oil-base paints and latex paints containing polyvinyl acetate-acrylic as the binder. The total annual economic damage to exterior household paints was estimated at $540 million (1972 prices), including paint loss and a labor factor of three times the cost of the paint.

Salmon[6] estimated that the annual cost of soiling of household paint would be $35 billion if surfaces were maintained as clean as they are in a clean environment (aesthetic costs). The annual cost of deterioration damage to paints was estimated to be $1.2 billion (direct costs). A 1974 study by Midwest Research Institute[4] recalculated the annual cost of damage to be $22 billion for soiling and $753 million for deterioration. These figures appear to be based on Salmon's hypothetical situation evaluation, which has been criticized as unrealistic. With a total cost of $2.5 billion for annual production of household paints, the damage far exceeds the production cost, even with a labor factor of 6 to 8.

Michelson and Tourin[9] investigated the frequency of house repainting as a function of suspended particulate concentration using a Comparative approach. Questionnaires were sent to residents of three suburbs of Washington, DC (Suitland, Rockville, and Fairfax) and two cities in the upper Ohio Valley (Steubenville and Uniontown). Data were compiled from the questionnaires to show maintenance intervals for exterior repainting in each of the five communities, but paint types were not reported. In Steubenville, where the mean annual particulate concentration was 235 $\mu g/m^3$, the estimated repainting frequency was greater than once per year! In Fairfax, where the mean annual particulate concentration was 60 $\mu g/m^3$, repainting occurred every 4 years. Thus, maintenance frequency increased as particulate concentration increased, as shown in Figure 1.[9] Such a linear function seems suspicious since a plateau at the low and high extremes of particulate concentration should be expected. The results of this investigation suggest that although a significant relationship exists between frequency of repainting and particulate concentration it is difficult to quantify by simple survey techniques. The survey results may

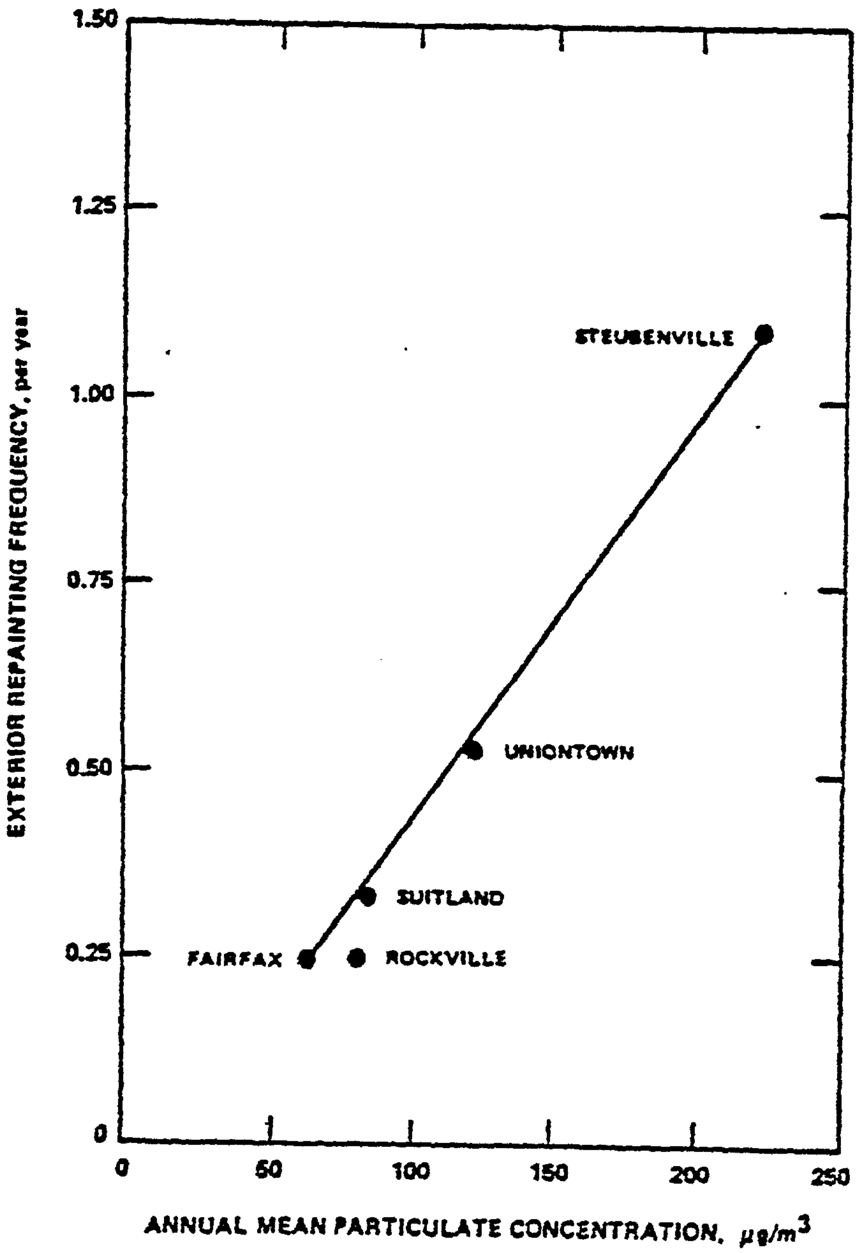

Figure 1. Indicated relationship between maintenance frequency for exterior repainting and particulate concentration.

Source: Michelson and Tourin (1967).

have been skewed by the fact that people who had repainted recently were more likely to respond than those who had not.

It would appear that additional maintenance data are needed, particularly for cities with mean annual particulate concentrations greater than 150 $\mu g/m^3$, to establish a more definite correlation. In addition, any correlation of frequency of repainting with concentration of particulate matter must take into account the fact that SO_2 is usually present in high concentration where particle counts are high. Thus, the cities in question were not sufficiently well matched for a simple comparative analysis.

Booz Allen and Hamilton,[10] in a study conducted for EPA, reported on painting maintenance frequencies in several zones of the Philadelphia metropolitan area with different population characteristics, climates, and types of industry. Socioeconomic factors were delineated by pollution zone; however, paint types were not reported. The percentage of households with incomes of less than $6000 increased with pollution level, a finding that may partially explain why there was no statistically significant correlation between painting frequency and particulate level found.

4.3 STRUCTURAL METALS

Type of damage: Corrosion, tarnishing.

Principal damage agents: SO_2, NO_x, TSP, other acid gases.

Other environmental factors: Moisture, salt.

Use of the material: The material is widely used in a variety of applications from tanks, buildings, and structural supports to roofing and vehicles. The material is generally selected due to its high strength per unit area and its durability rather than any aesthetic considerations.

The structural materials susceptible to damage by air polllution are zinc (galvanized), steel, and iron. Nonferous metals such as aluminum and copper, are relatively resistant to corrosion in the presence of air pollution, however, some studies have found that stress corrosion may be a more serious problem under some applications.[11]

Cost categories:

Direct: Both replacement and repair strategies are used in response to damage to structural metals. The relative importance of each in a given siguation depends on facotrs such as the effectiveness of repair in restoring complete functionality, the ratio of material costs and labor costs and especially on the economic lifetime of the structure made of the material in question. Structures or objects with economic lifetimes shorter or on the same order as the physical lifetime without repair are often allowed to deteriorate until replacement is required. However, in such cases, the effect of air pollution damage on the total lifetime is generally small. For example, automobiles usually suffer damage leading to a reduction of economic life from general wear and corrosion due to salt, moisture and abrasion much greater than that due to air pollution.

Avoidance: Costs for protection often constitute the major cost category for pollution damage to structural metals. The most common protection strategy is zinc coating (galvanizing) and/or painting. Costs for painting are especially important since a higher portion of such costs can be directly attributed to avoidance of pollution induced damage.

It should be noted that painting does not completely eliminate damage to metals. Defects in the paint surface, such as pin-holes or thin spots, can leave small areas effectively unprotected. Subsequent attack of the substrate leads not only to direct physical damage to the substrate, but accelerated damage to the rest of the protective coating. Thus, extra costs for surface preparation as part of an overall damage avoidance strategy are usually justified.[12]

<u>Aesthetic</u>: As with painted surfaces, the aesthetic cost of seeing an "unsightly" corroded surface is real but difficult to quantify. In fact, new steel alloys which form a non-damaging coat of oxidation products are rapidly being seen as aesthetically pleasing. An ironic twist is that such steel alloys actually require a small amount of sulfur oxide pollution in the air in order for the surface to form properly. If such material is used in a pristine environment, it suffers unacceptably rapid deterioration.

<u>Previous studies</u>: Spencer and Haynie,[13] in a chamber study of the effects of pollutants on galvanized steel, determined that clean air corrosion rates ranged from 1.14 μm/yr to 37.17 μm/yr over a range of relative humidities and temperatures.

The corrosion rates for clean air and polluted air were found to be very similar, however, the corrosion function which occurred was different for the clean atmospheres. In the case of the clean atmospheres the corrosion function was described as "pitting" as a result of the moisture nucleation at the end of wet and dry cycles. Galvanized steel in the outdoors, when only partially dry will develop this type of pitting regardless of the absence or presence of SO_2. The authors concluded that the corrosive effects of polluted environments on galvanized steel are not additive to the corrosive effects noted under clean air conditions. However, corrosion due to both "clean air" interactions noted in the experiments and that due to SO_2 will occur simultaneously during outdoor exposure of steel panels in the real world, making it difficult to distinguish material damage due exclusively to SO_2 concentrations.

Possible synergistic effects on metals have been found in atmosphere containing particulate and SO_2, as well as ozone and NO_x. Thus it is very difficult to isolate separate effects due to natural occurrences and air pollutants on materials exposed outside.

Damage estimates and subsequent economic costs due to the effects of air pollutants on material suffer from a large number of flaws. A typical cost estimation approach, such as the one performed by Salmon,[6] uses annual production of the material multiplied by a hypothetical factor (representing the assumption of exposure). No allowance is made for those materials upon which protective coating, such as paint, is applied or for naturally occurring degradation.

Painting of structural steel in bridges was investigated by Moore and O'Leary;[14] the practice involves sandblasting the steel to produce a rust-free surface and to remove mill scale. Without such surface preparation, water is immediately absorbed and sets up a corrosion system, rusting occurs, and the paint surface deteriorates in 2 to 3 years. The metal surface is protected by a primer that inhibits rust formation, and the primer coat is covered with two coats of SO_2-resistant paint, such as vinyl resin, which is substantially more expensive than household paint. Banov[15] estimated the cost of sandblasting at 25¢/ft^2 and the total labor cost at four to five times the cost of the paint. The cost of painting structural steel to give a service time of 10 years or more in urban areas can be as high as $1 to $1.25/ft^2. Michelson and Tourin[9] estimated the extra cost of paint application on external steel structures at $250 million.

A recent study published by the U.S. Department of Commerce[16] estimated that metallic corrosion cost $70 billion in the United States in 1975. This study used a modified version of the Battelle Columbus Laboratories National Input/Output Model, and the results were subjected to an uncertainty analysis by the National Bureau of Standards. The model, which incorporated a broad range of cost items (e.g., materials, labor, energy, and technical capabilities), indicated a total annual corrosion cost of $82 billion. However, the cost of corrosion specifically associated with ambient air pollution was not separated from other types of corrosion. Uncertainty in the total corrosion cost figure was estimated at ± 30 percent. Analysis suggested that avoidable costs of metallic corrosion represent about 15 percent of the total, but could range from 10 to 45 percent.

Roebuck and McCage[17] estimated that $15 billion in corrosion losses occur annually in the United States, largely from the corrosion of steel. The National Commission on Materials Policy[18] estimated that $5 billion could be saved annually by using known procedures to decrease corrosion of industrial steel, such as sandblasting the surface before painting and applying two coats of paint, which would protect the metal for many years with little maintenance.

Fink et al.[19] estimated that corrosion caused by air pollution of external metal structures costs $1.45 billion annually.

4.4 ELECTRICAL COMPONENTS

Type of damage: Corrosion, tarnishing.

Principal damage agents: SO_x, NO_x, other acid gases, polymerizable organic gases, particulate matter.

Other environmental factors: Moisture, salt.

Uses of the material: Contacts and components are made from a wide variety of metals; primarily gold, silver, and copper. Air pollutants can cause air insulating film to form on the metal components, resulting in failure of the components. Accumulation of particulates can cause defects in manufacturing or, in extreme cases, short circuits in components in use.

Cost categories:

Direct: Since the costs associated with the loss of service of electrical components is so high, damage extensive enough to necessitate replacement or repair is rarely allowed to accumulate. Problems with electrical components functioning in polluted atmospheres were recognized in the distant past, resulting in design changes and use of different materials which function adequately in these environments. For example, when the relay springs in telephone exchanges began to suffer breakage due to nitrate induced stress corrosion, a new spring alloy was developed and the problem ceased to be important. This one-time direct cost to solve the problem is not a significant cost of air pollution damage when such costs are averaged of a period of years. The costs of the new spring alloy were not significantly different than for the old one so there is not even a continuing avoidance cost. In any case, new solid state switching technology has largely supplanted mechanical relays and made the whole question moot.

Avoidance: Costs to avoid damage constitute the major category of pollutant damage costs. The greatest portion of these costs is attributable to protection (in the form of enclosed, controlled environments) and substitution of non-corroding materials (generally precious metals) for simple conductors. In both cases, the degree of damage acceptable is so low that similar if not exactly the same measures would be necessary even in the absence of significant ambient air pollution.

Aesthetic: Since most electrical components are primarily utilitarian, little to no aesthetic costs are incurred by their damage, except for the inconvenience due to loss of service.

Previous studies: Robbins[20] estimated that 15 percent of the gold and platinum used in the United States for electrical contacts in 1970 was for the specific purpose of combating SO_2 corrosion, with the remainder going for protection against other environmental pollutants. The use of palladium in electrical components has presented a problem in that it acts on compounds derived from plastics to catalyze the formation of an organic polymer film which acts as an insulator.

In areas where electrical instrumentation and computers are used, air is dehumidified and purified to help protect against corrosion. Robbins[20] suggested that the use of activated carbon filters and high-efficiency fine particle filters represents a cost attributable to SO_2 and particulate contaminants, as itemized in Table 3.

TABLE 3. COSTS ATTRIBUTABLE TO SO AND PARTICULATE CONTAMINANTS IN THE ELECTRONIC COMPONENTS INDUSTRY

	Millions of dollars 1970
Use of precious metals	20
Protective measures--filters and air conditioning	25
Loss due to failures	10
Research	5
Total	60

These estimates may overstate the costs since the benefits gained from the actions taken extend beyond protection from just SO_2 and particulate matter. In addition, since the physical damage function is not a single linear relation of damage and concentration, (i.e., even the smallest amount of damage is significant), the costs are likely to be unchanged by any feasible reduction in pollutant level, and can thus be considered independent of pollution.

4.5 FABRICS

Type of damage: Reduced tensile strength, soiling, fading.

Principal damage agents: SO_2, NO_2, O_3, TSP, other acid gases.

Other environmental factors: Sunlight, moisture, temperature, mildew, physical wear.

Uses of the material: Fabrics are used both indoor and outdoor in clothing, home furnishing, etc. The costs associated with pollution effects on fabrics can be determined from the outdoor exposure of material, which is extremely limited. For clothing and other textile materials used indoors, air pollution can only be considered a real factor for curtains.

In most cases, the economic lifetime of fabrics and textiles is so low that economically significant pollution damage is minor.

Cost categories:

Direct: Replacement and repair of fabrics is usually so dominated by physical wear or style that most pollution induced degradation is negligible. Rare instances of extreme pollution episodes leading to short term damage such as runs in nylon hose *or* tearing of heavier fabrics are generally associated with special and localized problems and not general ambient air quality. Accidental releases of acid mists and smuts are typical of such cases.

The only significant chronic problem attributable to ambient air quality is soiling. Such soiling is generally indirect, that is it results from contact with surfaces which had been soiled over relatively long time periods. Since the direct costs of cleaning soiled fabrics depends on a number of individual tastes and standards, they are extremely difficult to predict as a function of ambient pollution, level.

Avoidance: There is little that can be done to avoid pollutant damage to fabrics. The degree of damage is not generally sufficient to justify extensive air cleaning measures by themselves. Coatings which provide better soil release are generally used to protect against spills rather than direct or indirect air pollution impact. Substitution with more resistant materials is generally not implemented (except possibly in the case of reformulation of nylon polymers used in hosiery with more resistant varieties). In fact, the trend away from relatively resistant materials such as linen, wool and cotton toward more susceptible materials such as nylon and polyester indicates that the cost and other advantages of the newer materials outweighs the increased susceptibility to air pollution.

Aesthetic: The principal aesthetic cost is related to uncorrected soiled appearance and limitations on the colors or textures appropriate to life in a polluted environment.

Previous studies: The chief problem with prior economic estimates is that a large proportion of fading and physical wear were attributed to pollution rather than other environmental factors. Surveys of use and impact have found that:

- For most textiles, the lifetime of the material is determined primarily by the amount of exposure to sunlight, humidity level, and fashion changes rather than air pollution.
- For most indoor and outdoor textile soiling, leading to a greater frequency of washing or cleaning, is governed by factors other than TSP levels. The only major exception is likely to be curtains, in which case the cleaning frequency is more likely to be determined by habit rather than appearance.
- There is, basically, very little realistic, quantitative information relating pollutant levels to loss of strength of different fabrics exposed at outdoor locations.

According to Brysson et al.[21] high pollutant levels (mean sulfation 5 mg $SO_3/100\ cm^2/day$ and/or SO_2 concentrations of 0.2 ppm or 520 $\mu g/m^3$) can reduce the effective life to one-sixth when compared to low pollution sites (0.5 mg $SO_3/100\ cm^2/day$ and/or 0.02 ppm or 60 $\mu g/m^3$ SO_2 concentrations).

Of the 1.257 trillion pounds of fiber used for industrial purposes in 1965, the Textile Organization reported that 583 million pounds were cotton and that 300 million pounds had the outdoor uses shown in Table 4.

TABLE 4. AMOUNTS OF COTTON FIBER USED FOR VARIOUS OUTDOOR PURPOSES

Use	Amount, 10^6 lb
Automotive upholstery and seat covers	56
Fire hose	20
Cordage	56
Tarpaulins, tents, awnings, etc.	70
Bags and bagging	63
Miscellaneous (agricultural cloth, flags)	35
Total	300

In a report of a telephone survey of consumer awareness of damage to textiles due to air pollution, Upham and Salvin[22] noted that Philadelphia respondents did not perceive soiling of fabrics as a damage effect. There was a reluctance to communicate this type of information, which is somewhat personal. The work done during the early 1970s and late 1960s to quantify the costs associated with loss of serviceability of material through decay and fading represent an overreaction and oversimplification of the actual problem.

4.6 PLASTICS AND ELASTOMERS

Type of damage: Cracking, weakening.

Principal damage agents: Ozone, oxidants.

Other environmental factors: Sunlight, temperature.

Uses of the material: Plastics are used for a wide variety of material application ranging from automobiles to calculators. In the past plastics were considered as substitute materials for substances such as wood, leather, horn or shell, ivory, rubber, and paper. However, as the range of properties available in synthetic polymers increased and surpassed those of any previously known "natural" material, plastics began to be used for a variety of purposes made possible only by their existence. The state-of-the-art of polymer science is advanced to the degree that new materials are specifically designed for new uses. The result has been an incredible variety of uses for these materials and a high rate of change in both the materials in use and uses themselves. Due, in part, to the volatility of the situation, any estimates of economic damages on plastics is purely guesswork, since neither the damage function nor the exposure distribution are defined. In general these products are designed and built to function for periods of time consistent with their economic lifetime in polluted environments. Therefore, the economic loss due to the effects of pollution on these materials is minimal since an appropriate design factor has already been incorporated.

Cost categories:

Direct: The major fraction of direct costs is related to replacement rather than repair of plastics and elastomers. However, as stated above, the material is usually designed such that its response to pollution is not consequential relative to the economic lifetime of the product of which it is a part. A possible exception may be rubber tires. Increased side-wall failure can result from high ozone levels, especially in hot climates. However, the influences of sunlight and temperature are so strong that it is difficult to separate them from the pollutant damage and thus assess the role of pollution in increased costs.

Avoidance: Most cost avoidance strategies for damage to plastics and elastomers are built-in; that is, the formulation of the material itself was designed with pollution resistance in mind. The cost of such formulation considerations is difficult to define since the rapid changes in the field due to other factors results in such rapid turnover in materials use that few products are substituted strictly for air pollution reasons.

The most significant problem with understanding the effects of air pollutants on plastics is:

- the lack of data, since no studies exist that qualitatively show any cause and effect relationships;
- the overwhelming impact of environmental factors such as temperature and sunlight on the durability of the material.

Aesthetic: While some would consider the use of plastics itself an aesthetic cost, such an attitude is apparently not widespread. The short lifetimes associated with most plastic and elastomer products also reduces the likely aesthetic impact of any damage.

Previous Studies: No significant studies of the economic impacts of pollution damage to plastics and elastomers are available. What information is available is generally based on unsubstantiated assumptions, and as such constitute little more than guesses.

4.7 NON-METALLIC BUILDING MATERIALS

Type of damage: Soiling, discoloration, surface breakage or spalling, rot.

Principal damage agents: TSP, SO_2, acidic gases.

Other environmental factors: Moisture, freezing and thawing, microorganisms.

Use of material: Brick, glass, concrete, stone and wood are used for both structural and decorative uses. As such, the appearance, as well as the structural integrity, of each is important. Although dissimilar in many respects, each of these materials tends to be exposed to similar environmental conditions for similar purposes, that is they form the exterior shell of buildings.

Cost categories.

Direct: With the possible exception of marble, none of the materials has well defined physical damage functions for irreversible damage related to ambient air pollution. All can suffer from soiling and discoloration, and the costs incurred for changing can be significant. However, except for glass, changing is done on an infrequent basis and is generally not part of a routine maintenance program. These cleaning costs, like similar costs for other materials, are highly variable and dependent on aesthetic considerations. Since the cleaning of a building usually represents a major undertaking, an interesting inversion in normal practice is often observed. As TSP pollution decreases, expenditures for cleaning increase. At high pollution levels, the appearance is degraded so quickly that the cost of cleaning is not justified. As pollution levels decline, the forgone maintenace is perceived as worthwhile and is implemented.

Avoidance: In extreme cases, where pollution is rapidly causing degradation of buildings, such as the marble structures in Greece and Venice, protection of the surface with silicone oils or other coatings is being considered. However, these measures are only being considered for special structures and are not part of general practice. As discussed in other sections, substitution of one material for another with a number of significantly different characteristics is generally not considered a substitution strategy for avoidance of damage costs.

Aesthetic: The fact that some materials, such as light colored or carbonate rich stone are no longer considered suitable for building can be considered a potential aesthetic loss. However, as people become accustomed to, and eventually begin to prefer the materials which are more suitable, the effective sense of loss diminishes.

The inconvenience of soiling, especially on windows where a high degree of cleanliness is desirable, can be considered an aesthetic cost. However, in most cases it can be assumed that the costs incurred for cleaning is roughly sufficient to keep the uncompensated aesthetic costs low.

Previous studies: Although studies of the potential damage to substances such as concrete have produced high economic damage estimates, they are generally flawed to such an extent that their basic conclusions are of doubtful validity. The main problem is the lack of documented physical damage functions relating exposure to pollutants to significant damage. Simply assuming a given percent of the total maintenance and replacement costs is attributable to pollution damage is not sufficient or reasonable in the absence of any data.

4.8 WORKS OF ART AND HISTORICAL MONUMENTS

Type of damage: Fading, corrosion, spalling, soiling.

Principal damage agents: SO_2, NO_x, TSP, other acid gases.

Other environmental factors: Moisture, sunlight, temperature, physical wear.

Use of material: The types of materials involved represent an extremely wide variety ranging from metals and building stone to fabrics and paint. The type of damage suffered by an object is a function of the material of which the object is made and the way in which the importance of the object is affected by damage,

Cost categories:

Direct: Since some types of damage are irreversible and the objects destroyed are irreplaceable, there is a great concern regarding the loss of this historic and artistic value. The costs for these objects cannot be quantified due to their irreplaceable nature.

Even repair can destroy some of the intrinsic value of an art object or object of historical importance. Cleaning can be an important factor, but since preservation is often of higher importance than appearance, even this strategy is sometimes forgone to avoid damage.

Avoidance: The major monetary effect of pollution damage to art or historical objects is avoidance costs. Providing controlled, protective environments is a common practice and in some cases, application of protective coatings is attempted. Some portion of these protective measures are also useful in protecting against other environmental factors and should not be assessed as a cost of pollutant damage alone.

Aesthetic: By far the greatest cost incurred by society is the aesthetic cost of the loss or irreparable degradation of these objects. But since such costs grow even greater with the passage of time, and there is no definable economic lifetime for a truly important work of art or historical object, the total costs are incalcuable.

Previous studies: Although damage to works of art and historical objects has been addressed in general terms by Yocum et al.,[18] no thorough attempt has been made to quantify the economic loss suffered due to air pollution effects. Due to the complex and aesthetic nature of the problem, there is some doubt whether such an estimate is even possible.

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